

CHAPTER 1

INTRODUCTION

The majestic peaks of central Andes of Peru, Bolivia and northern Chile support thousands of small glaciers. At present, these glaciers are in a state of pronounced retreat. If the current rates of retreat continue many may disappear within the next century. The causes of this dramatic retreat are presently unknown, but are part of a globally pervasive pattern of glacial retreat consistent with other evidences for global warming (Oerlemans, 1994). In the central Andes, this retreat has economic ramifications as glaciers are a valuable water resource for hydroelectric power, irrigation and human consumption as well a source of recreation and tourism (Francou *et al.*, 1995; Jordan, 1991; Ribstein *et al.*, 1995).

Past changes in these glaciers are of interest as well. Glacier changes are one of very few lines of evidence that can be used to infer what the climate of the central Andes was like in the past. A major unresolved question in the study of Quaternary paleoclimates is what the climate of the tropics was like during the late Pleistocene glacial maximum. Abundant geomorphic evidence shows that modern glaciers in the central Andes are diminutive compared to the glaciers that existed during the late Pleistocene. These late Pleistocene paleo-glaciers were larger, more numerous, and extended to considerably lower elevation than those at present. The elevational difference between modern and late Pleistocene glaciers, known

as a snowline depression, is a measure of climate change. The amount of snowline depression observed in the central Andes indicates that the temperature in the region during the late Pleistocene was 5-9° C cooler than at present.

This cooling is in agreement with other estimates of late Pleistocene climate from tropical South America including ice cores records from Peru (Thompson *et al.*, 1995), elevational changes in treelines in the northern Andes (Hooghiemstra *et al.*, 1992; van der Hammen, 1988), and noble gases dissolved in groundwater in the Amazon Basin (Stute *et al.*, 1995). However, it is difficult, if not impossible, to reconcile the temperature changes recorded at these tropical continental sites with the sea surface temperature estimates for the late Pleistocene developed by CLIMAP (1976; 1981).

Remote sensing coupled with topographical analysis is a powerful tool that can be used to monitor present changes in the glaciers of the central Andes as well as to map the extent of late Pleistocene glaciers based on geomorphology. Through the use of remote sensing and geographic information systems (GIS) technologies, the glaciers that existed in the central Andes can be reconstructed in detail and over an area otherwise impossible. Remote sensing can also be used to complement the few ongoing field studies in the region, providing information on the extent and surface conditions of many more glaciers than is otherwise possible. This thesis uses

remote sensing and digital terrain analysis to study modern and late Pleistocene glaciers in the central Andes.

Chapter 1 reconstructs the climate in the central Andes at the time glaciers were at their late Pleistocene maximum extent. The elevation of the late Pleistocene snowline is constructed in a detail not previously possible using cirque floors in Peru and the extents of glaciers mapped from Landsat Thematic Mapper (TM) images between 15° and 22° S latitude. Comparing the elevation of the late Pleistocene snowline with that at present reveals that snowline depression was variable over the region, ranging from 500 to 1200+ meters. A simple mass balance model is used to examine the temperature and precipitation changes that could account for the observed snowline depression. The observed snowline depression is best explained by a cooling of 5 to 9°C. Glacier expansion in the arid western cordilleras, where glaciers today are limited by precipitation, indicates wetter conditions existed as well.

The analysis of paleo-glaciers is extended in Chapter 2. This chapter details the Landsat TM based mapping of glacial moraines between 15° and 22° S that has been conducted over the past several years. At the time of maximum glacier extent, the central Andes at these latitudes contained approximately 11,000 paleo-glaciers with an calculated area of 29,800 km² and an estimate volume of 3700 km³.

The final two chapters use remote sensing and digital terrain analysis to study modern glaciers in the central Andes. Chapter 3 details the

application of spectral mixture analysis to map the accumulation and ablation areas of Zongo Glacier, Bolivia, and the Quelccaya Ice Cap, Peru. The transient snowline, which lies at the boundary between the two, can be identified. At the end of the ablation season, the elevation of the transient snowline is a good approximation of the Equilibrium Line Altitude (ELA). Thus this technique offers the ability to monitor relative changes in the ELA over time for many more glaciers than is possible using traditional field methods.

Chapter 4 examines the relationship between magnitude of incident shortwave radiation and the distribution of glaciers in a portion of the Cordillera Real, Bolivia. A digital elevation model is used to model topographically induced variations in incident shortwave direct and diffuse radiation throughout the year. Today, glaciers are found in areas of the landscape that receive the lowest amounts of incident shortwave radiation.

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